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LOCAL GROUP DWARF GALAXIES AND THE FUNDAMENTAL MANIFOLD OF SPHEROIDS

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ABSTRACT

The fundamental manifold (FM), an extension of the fundamental plane formalism, incorporates all spheroid-dominated stellar systems from dwarf ellipticals up to the intracluster stellar populations of galaxy clusters by accounting for the continuous variation of the mass-to-light ratio within the effective radius r_e with scale. Here, we find that Local Group dwarf spheroidal and dwarf elliptical galaxies, which probe the FM relationship roughly one decade lower in r_e than previous work, lie on the extrapolation of the FM. When combined with the earlier data, these Local Group dwarfs demonstrate the validity of the empirical manifold over nearly four orders of magnitude in r_e. The continuity of the galaxy locus on the manifold and, more specifically, the overlap on the FM of dwarf ellipticals like M 32 and dwarf spheroidals like Leo II, implies that dwarf spheroidals belong to the same family of spheroids as their more massive counterparts. The only significant outliers are Ursa Minor and Draco. We explore whether the deviation of these two galaxies from the manifold reflects a breakdown in the coherence of the empirical relationship at low luminosities or rather the individual dynamical peculiarities of these two objects. We discuss some implications of our results for how the lowest mass galaxies form.

Subject headings: galaxies: formation — galaxies: elliptical and lenticular — galaxies: fundamental parameters — galaxies: structure

1. INTRODUCTION

Scaling relationships among galaxies provide many of the principal constraints on galaxy evolution models. As such, the "fundamental manifold" of spheroids (hereafter FM; Zaritsky et al. 2006), which spans a factor of 1000 in effective radius r_e and of 100 in velocity dispersion σ, poses a challenge to models of the formation of kinematically hot stellar components embedded in dark matter halos. Zaritsky et al. (2006) focused principally on relating the structural properties of the spheroidal stellar component of the largest known virialized systems, the intracluster stars of galaxy clusters (CSph; Gonzalez et al. 2005), to those of more common spheroids such as giant (E) and dwarf (dE) elliptical galaxies. They considered the efficiency with which baryons are packed relative to dark matter within r_e (as measured by the mass-to-light ratio within $r_e, M_e/L_e$) and found that the existence of the spheroid FM implies a $M_e/L_e - \sigma$ relationship that continues to steepen with σ from Es to CSphs. In other words, the packing of baryons relative to dark matter within r_e is less efficient for these spheroids as σ increases. The behavior for spheroids with still smaller values of σ, dEs and dwarf Spheroidals (dSphs), was inconclusive. In this Letter, we consider this low-σ extreme of spheroid scale, using eight Galactic dSphs and four dE companions of M 31 to investigate how well the smallest and most compact galaxies map onto the extrapolation of the FM. Finally, we speculate on how the behavior of the FM for these lowest mass galaxies might be used to constrain galaxy formation models.

2. RESULTS AND DISCUSSION

We searched the literature for the necessary data for every dwarf elliptical and spheroidal in the Local Group. The data (Table 1, Figure 1) come from various sources. We calculate the half light radii for the Galactic dwarf spheroidals using the King model fit parameters given by Irwin & Hatzidimitriou (1995). For the Andromeda systems, we adopt the r_e given by Kent (1987) for M 32 and NGC 147, fit to Kent's photometry for NGC 185, and use the value given by Choi et al. (2002) for NGC 205. The mean surface brightness within r_e, I_e, is evaluated using the total luminosity and a circular aperture defined by r_e. For consistency with the data used by Zaritsky et al. (2006), we convert magnitudes from V to Cousins I using the color transformation for ellipticals from Fukugita et al. (1995). We do not attempt to correct r_e for any possible color dependencies. The errorbars represent the propagated uncertainty due to the quoted statistical errors in σ, the apparent magnitude, and the distance. Errors in the half-light or effective radius are not included as they affect both the ordinate and abscissa such that the data points move nearly parallel to the projection of the fundamental manifold (see Figure 1 for a demonstration). The velocity dispersion uncertainties are the dominant source of the plotted errors.

We compare the position of these 12 dwarfs to the FM of Zaritsky et al. (2006) in Figure 1. We have not modified the old relationship to optimize the fit to this new set of points. The χ^2_ν value of only these new data with respect to the existing model is 1.91. This value is high, even for the relatively small sample given here (such a value can be ruled out as random with > 98% confidence). However, this apparent discrepancy is due solely to Ursa Minor (UMi) and Draco (without these two galaxies, χ^2_ν drops to 0.82).

Apart from the two outliers, which are discussed in more detail below, the other 10 systems extend the FM relation nearly a decade lower in effective radius. The

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continuity of the locus of spheroids on the FM, from CSphs to dEs, suggested a single family of spheroids (Zaritsky et al. 2006). The overlap here between dEs and the Galactic dSphs indicates that even dSphs are part of this family. A further example of the continuity of spheroid properties on the FM is that one of the highest surface brightness galaxies known, M 32, lies next to one of the lowest surface brightness galaxies, Leo II. These two galaxies also differ in velocity dispersion by nearly a factor of ten. M 32's presence on the FM suggests that unless tidal stripping works to move objects along the FM, M 32 has been only modestly disturbed by its interaction with M 31 (a similar conclusion is reached through other arguments by Choi et al. 2002).

We note that even for the 10 dwarfs that are statistically consistent with the FM extrapolation, there may be a small but systematic deviation. All but one of the dwarf galaxies lie above the FM projection, while at larger values of r_e ($1 < \log r_e < 2$, r_e in kpc) the data appear to lie systematically below the line. These systematic deviations may indicate that there is a more precise fit to the global FM than that presented by Zaritsky et al. (2006). However, given the uncertainties in the measurements (see the scatter in published m_V values for the Galactic dSphs in Table 1), the possible systematic behavior of r_e with color, the use of a single universal color term across the entire range of systems, and the difficulties in defining σ, it is premature to fine-tune the FM coefficients.

Returning to the two outliers, Draco and UMi, we discuss three possible causes (in order of least to most astronomically interesting): 1) the difficulty in measuring the basic fundamental parameters of these systems has been underestimated, leading to overly optimistic errorbars or to systematic errors, 2) these two galaxies are experiencing tidal forces that affect their internal kinematics and structure such that they no longer lie on the FM, or 3) these two galaxies, which have the lowest luminosities of all the galaxies in the sample, mark the breakdown of the tight FM relationship at low luminosities, and so identify the location in this parameter space at which baryons and dark matter no longer follow the same "rules" of galaxy formation.

If the offset between these two galaxies and the FM is due to Option 1, then the large value of χ^2_ν must be attributed to a problem with the velocity dispersion measurements and/or their estimated uncertainties. Errors in the apparent magnitude and distance are unlikely to cause such a large discrepancy. For example, to bring Draco back onto the FM requires an error in the absolute magnitude of 2.86 mag. Even though one could parcel this error into errors in the apparent magnitude, color conversion, and distance, these errors would still be unreasonably large. Alternatively, one could place Draco on the FM with a modest change of its velocity dispersion from 8.5 (Armandroff et al. 1995) to 5 km sec^{-1}. Is such a systematic error likely?

Measurements of the velocity dispersions of dSphs have improved greatly over the past two decades and now come from samples of hundreds of stars. The quoted uncertainty on the measurement we use is 0.7 km sec^{-1} (Armandroff et al. 1995), so the required change in σ from 8.5 to 5 km s^{-1} appears unlikely on purely statistical grounds. Recent, larger studies (Kleyna et al. 2002; Muñoz et al. 2005) confirm the global velocity dispersion from Armandroff et al. (1995), although they do find radial gradients in σ. The velocity dispersion used in the FM relationship is supposed to be that measured within r_e, although we generally assume flat dispersion profiles and adopt the measured global value. The dispersion profile presented by Muñoz et al. (2005) suggests that σ could be as low as ~ 6 km sec^{-1} over a centrally limited radius, which could help to reconcile Draco's position relative to the FM. However, UMi has a velocity dispersion gradient of the opposite sign, so its central σ is larger than the global value. Taking a more central value for σ would increase the discrepancy between UMi's location in Figure 1 and the FM. We conclude that although the newly identified velocity dispersion gradients complicate the picture (and so perhaps lessen the discrepancy by increasing the errorbars), they do not act in a systematic manner to address the current discrepancy between the FM and the properties of UMi and Draco.

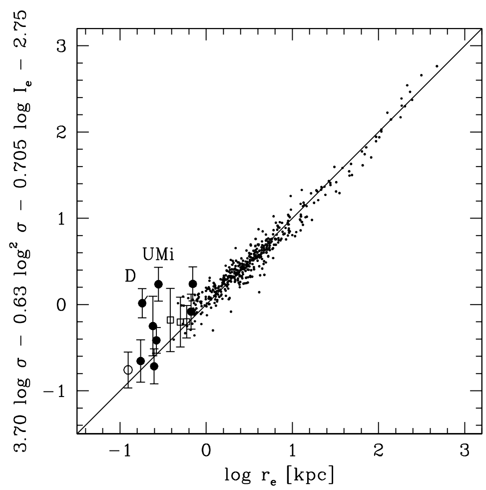

FIG. 1.— Local Group spheroids plotted on the fundamental manifold. The small dots represent the data presented in Zaritsky et al. (2006), which include the intracluster stellar component of galaxy clusters (CSph), brightest cluster galaxies (BCG), giant ellipticals (E), and dwarf ellipticals (dE). The filled circles with errorbars represent the eight Galactic dwarf spheroidals, with the two vertically outlying points representing Ursa Minor (UMi) and Draco (D). The open symbols represent the four M 31 satellites (the open circle at the bottom left of the Figure represents M 32). The solid line is the edge-on projection of the manifold in this coordinate system as derived by Zaritsky et al. (2006). The short diagonal line extending from the Draco data point represents the change in position caused by adopting the structural parameters of Odenkirchen et al. (2001) rather than those from our calculations using the Irwin & Hatzidimitriou (1995) King model fit.

Proceeding to Option 2, we can speculate that these two systems are not well described by simple dynamics. They are the two closest galaxies to the Milky Way among our set, as well as the two of lowest luminosity. Because of these properties, it is often suggested that Draco and UMi are victims of tidal stripping (Kuhn & Miller 1989; Kuhn 1993; Kroupa 1997; Fleck & Kuhn 2003; Gómez-Flechoso & Martínez-Delgado 2003; Muñoz et al. 2005). For example, Muñoz et al. (2005) argue that this galaxy is not a simple, dynamically

TABLE 1
Local Group Spheroids

Name	r_e [arcmin]	m_V	m_V Range	σ_v [km s^{-1}]	D [kpc]	References
Ursa Minor	14.5±1.1	10.3±0.4	9.8-10.69	8.8±0.8	66±3	1, 9, 12
Draco	8.2±0.7	10.9±0.3	10.78-11.0	8.5±0.7	76±6	1, 5, 9, 15
Sculptor	11.5±1.9	8.5±0.3	8.13-8.8	8.8±0.6	79±4	9, 12, 19, 20
Sextans	28.0±5.8	10.3±0.3	10.2-10.4	6.2±0.7	86±4	9, 12, 16
Carina	8.2±1.1	10.85±0.25	10.6 -11.0	6.8±1.6	101±5	9, 11, 12, 13
Fornax	16.7±1.0	7.6±0.3	6.9-8.4	12.4±1.5	138±8	9, 12, 19
Leo II	2.6±0.4	12.0±0.2	11.6-12.0	6.7±1.1	233±12	3, 9, 12, 18
Leo I	3.4±0.4	10.1±0.3	10.0-10.2	8.8±0.9	254±30	2, 9, 12, 14
NGC 185	2.50	9.09±0.15	...	28±8	620±25	8, 10, 12
NGC 147	2.13	9.35±0.15	...	23±5	725±45	4, 10, 12
M 32	0.53	8.10±0.15	...	60±10	805±35	6, 10, 12, 17
NGC 205	2.38	8.05±0.15	...	35±5	815±35	6, 7, 10, 12

References. — [1] Armandroff et al. (1995), [2] Bellazzini et al. (2004), [3] Bellazzini et al. (2005), [4] Bender et al. (1991), [5] Bonanos et al. (2004), [6] Choi et al. (2002), [7] Geha et al. (2006), [8] Held et al. (1992), [9] Irwin & Hatzidimitriou (1995), [10] Kent (1987), [11] Mateo et al. (1993), [12] Mateo (1998), [13] Mateo et al. (1998b), [14] Mateo et al. (1998a), [15] Odenkirchen et al. (2001), [16] Suntzeff et al. (1993), [17] van der Marel et al. (1994b), [18] Vogt et al. (1995), [19] Walker at al. (2006), [20] Westfall et al. (2006)

Note. — The effective radii were determined using the King model fit parameters from Irwin & Hatzidimitriou (1995) for the Galactic dSphs and from the data of Kent (1987) for NGC 185. Other data are drawn directly from the references.

relaxed system because of the unphysically large inferred mass (implying $M/L > 900$) based on their measurement of a large σ far from UMi's core. Such arguments favor the interpretation that the dynamics of these systems are somewhat disturbed, that the velocity dispersions are affected, and that these systems should lie off the FM. The critical test of this interpretation is to determine where other low luminosity spheroids, especially those far from the Milky Way or M31 and thus unperturbed by tidal forces, fall with respect to the FM.

There are at least two other Local Group objects that are particularly interesting for this discussion given their low luminosity: the Ursa Major dwarf (Willman et al. 2005) and And IX (Zucker et al. 2004). Unfortunately, the data are not yet of the quality necessary to impact this discussion. The magnitude and structural parameters of UMa are currently crude estimates, although improved data are on the way. If we do adopt the published structural parameters (Willman et al. 2005; Kleyna et al. 2005), then UMa lies well above the FM, as do UMi and Draco. The data for And IX are further along (Harbeck et al. 2005; Chapman et al. 2005), but the velocity dispersion is still somewhat problematic. The stellar velocity dispersion is almost zero at small radii and then rises quickly with radius. The global velocity dispersion value may therefore be misleading. Nevertheless, if we adopt the published value, we find that And IX is also above the FM relationship, although only by 1.1 standard deviations given the large uncertainty. Improving the data on these two galaxies is key because they probe the low-luminosity end of the spheroid distribution.

Finally, considering Option 3, we restate that Draco and UMi are the lowest luminosity galaxies plotted in Figure 1 and that the preliminary data discussed above for two other low luminosity dwarfs show consistent deviations from the FM. As such, Draco and UMi might be indicative of a breakdown in the coherence of the FM at these luminosities. Do we expect such a breakdown?

As discussed by Zaritsky et al. (2006), the trend of M_e/L_e with σ that leads to the FM can be physically interpreted as a trend in the packing efficiency of baryons relative to dark matter within r_e. They concluded that the packing is inefficient for the systems with largest σ (CSphs and BCGs), becomes highly efficient for systems with moderate σ (Es), and, with less certainty, becomes inefficient once again in systems with low σ (dEs). The continuation of the FM relationship here to even lower σ systems confirms that the packing of baryons relative to dark matter is highly inefficient in the systems with the lowest σ's. The key to a tight FM lies in the maintaining this pattern in the relative distributions of baryons and dark matter among all spheroids. If there is a class of spheroids for which a change in the distribution of baryons due to non-gravitational physics is not accompanied by a corresponding change in the distribution of the dark matter, we expect a loss of the FM coherence for those spheroids.

One such class may be systems in which the baryons are dynamically negligible and that therefore lack a physical connection between the properties of the baryonic (r_e, I_e) and dark (σ) components. If the baryons in these systems are subject to forces that do not affect the dark matter, such as winds or ram pressure stripping, the dark matter would not respond to changes in baryon distribution. In other words, the baryons can be distributed, or packed, within the dark matter halo in numerous ways without affecting σ, and this range of optical r_e's and I_e's will almost certainly break the coherence of the FM.

The baryons are dynamically negligible in low-luminosity systems with large mass-to-light ratios (see Mateo 1998) and where non-gravitational physics is expected to be important (Babul & Rees 1992; Martin

1999). As one example of how the FM coherence may be broken, we consider a population of dark-matter-dominated, low-luminosity systems in which varying fractions of baryons have been lost due to supernova winds. These systems will all have the same σ (because the dark matter properties are unaffected by the baryon loss), but different values of I_e. Unless r_e conspires to compensate for the change in I_e, this set of objects will lie off the FM by differing amounts. Upward scatter in Figure 1, as seen for Draco and UMi, corresponds to a lower than predicted effective surface brightness, as would arise if these dSphs are dark-matter-dominated and have experienced baryon loss.

The adherence or deviation of low-mass galaxies from the FM may ultimately help to address one of the key questions facing current hierarchical models — how do galaxies populate low mass halos? A wide range of literature has considered the "missing satellite problem" formalized by Moore et al. (1999) in which cold dark matter cosmological models apparently overpredict the number of low luminosity satellite galaxies. It is now evident that any solution to this problem must include a delicate balancing act to retain the FM well into the low mass regime where the problem has been identified. The tightness of the FM relationship down to at least the luminosity of UMi and Draco suggests that solving the missing satellite problem may require investigating two regimes, namely those in which baryons are and are not dynamically important. Processes that inherently generate significant scatter, such as any that are environmentally driven (see, for example, Kravtsov et al. 2004), could easily fail to reproduce the low scatter seen in the FM for systems more luminous than UMi and Draco. If the other hand, we were able to quantify the scatter along the vertical axis in Figure 1 for objects like UMi and Draco, then that scatter would constrain the variations in mass loss or star formation efficiency allowed as a function of σ.

3. SUMMARY

We demonstrate that the lowest luminosity, lowest surface brightness, and lowest velocity dispersion spheroidal galaxies currently known fall on the projection of the "fundamental manifold" (FM) defined by Zaritsky et al. (2006). The FM now spans nearly four orders of magnitude in effective radius r_e. The FM is not a simple recasting of the virial theorem, as demonstrated by the complex behavior of the mass-to-light ratio within r_e with σ (Zaritsky et al. 2006) that is now extended by these new data. The FM places a constraint on models of spheroid formation ranging from the dwarf spheroidals of the Local Group to the intracluster stellar component of rich galaxy clusters. In particular, the manifold describes an increase in the ratio of dark to luminous matter within the optically defined effective radius for both the largest and smallest spheroids embedded in dark matter halos. The continuity of this relationship into the regime of dSphs suggests that these systems are not a distinct class of spheroid and that they have not been grossly affected by interactions with their massive parent galaxy. The tightness of the FM well into the low mass regime, where the "missing satellite" problem arises (Moore et al. 1999), suggests that it may be challenging to explain the existing systems as the few sole survivors of a complex and violent history.

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